Laboratory Investigations and Numerical Modeling of Loss Mechanisms in Sound Propagation in Sandy Sediments

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Award Number: N00014-05-1-0225
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LONG-TERM GOALS

To develop accurate models for high frequency sound propagation within shallow water sediments.

OBJECTIVES

The scientific objectives are to: 1) quantify the relative importance of scattering and frictional losses in the attenuation of sound in the sediment, 2) evaluate and improve existing models of sound propagation and, 3) develop more complete models of sound propagation that can account for the complexity of shallow water sediments.

APPROACH

Recent experiments have suggested that at high frequencies in unconsolidated, granular media, the attenuation of sound may be due to both dissipation mechanisms at the grain contacts and scattering losses due to presence of heterogeneities in media [1,2]. While this may explain the attenuation observed at high frequencies in ocean sediments, such as that observed during the Sediment Acoustics Experiment 1999 (SAX99) and 2004 (SAX04) [3,4], a majority of the theories that have been developed to date have focused solely on losses at the grain contacts [5,6]. The work performed here examines the role of heterogeneities in the sediment that may scatter energy from the coherent fast compressional wave into slow compressional and shear waves, increasing the attenuation.

To understand the role of the heterogeneous nature of unconsolidated media, efforts have been made to develop models that account for the presence of force chains and porosity variations. These heterogeneities are incorporated into a Biot description of a sand sediment using perturbation theory. These heterogeneities have also long been believed to play a role in the scattering of sound from the sediment interface [7]. The theories of sound propagation being developed here may therefore be tied to theories of scattering from volume heterogeneities. To begin to explore this possibility, a series of high-frequency scattering measurements were made in the Naval Surface Warfare Center-Panama City (NSWC-PC) test pond on an artificially smoothed sand sediment. Extensive environmental characterization was also performed as well as sound speed and attenuation measurements in order to compare the two theories.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Laboratory Investigations And Numerical Modeling Of Loss Mechanisms In Sound Propagation In Sandy Sediments**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,Seattle,WA,98105**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
To develop accurate models for high frequency sound propagation within shallow water sediments

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

To account for heterogeneities in the frame bulk modulus of a poroelastic medium, perturbation theory was applied to Biot's poroelastic theory to account for the scattering of energy into incoherent fast and slow compressional waves. The resulting theory has been shown to be causal and the range of validity of the theory has been determined by considering higher-order scattering contributions. These results have been presented in a manuscript that has been submitted to the Journal of the Acoustical Society of America [8]. Perturbation theory has also been applied to a poroelastic medium that has heterogeneities in the porosity. The results of this theory were presented at the Acoustical Society of America Meeting in Portland, OR [9] and a manuscript that develops and discusses the theory is currently in preparation.

In order to explore the role of porosity heterogeneities in both sound propagation and scattering from the sediment interface, a set of preliminary high-frequency back-scattering measurements were made in the NSWC-PC test pond. These measurements leveraged the synthetic aperture sonar measurements being made by Dr. Steve Kargl using the APL-UW rail system. Backscattering from an artificially smoothed sand sediment was measured from 200 to 500 kHz using a set of piston sources and receivers mounted on the front of the rail tower as shown in Fig. 1. By smoothing the sand, the scattering due to surface roughness was significantly reduced and the dominant scattering mechanism is likely due to the volume heterogeneities within the sediment.

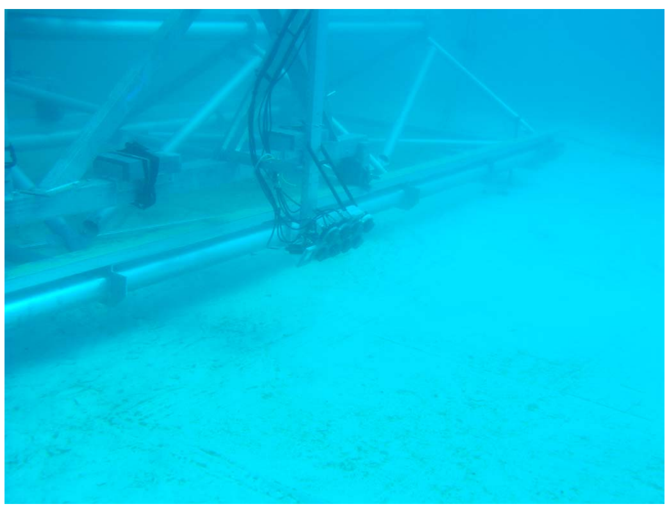

Figure 1. The scattering array mounted on the front of the APL-UW rail tower. The sediment in front of the rail was smoothed from the rail out to 5 m to minimize the scattering from the sediment roughness.

RESULTS

In the submitted manuscript, we were able to show that, for a given sediment, there is a range of heterogeneity statistics for which the perturbation theory is valid. For weakly consolidated sediments, such as a sand sediment, the theory predicts that for valid statistics, the sound speed and attenuation are only weakly affected by scattering from the heterogeneities. This can be seen in Fig. 2(a) for the SAX99 sediment parameters and variances that fall within the range of validity for the theory.

However, for consolidated sediments, such as a sintered glass bead pack, heterogeneities can produce significant scattering as seen in Fig. 2(b).

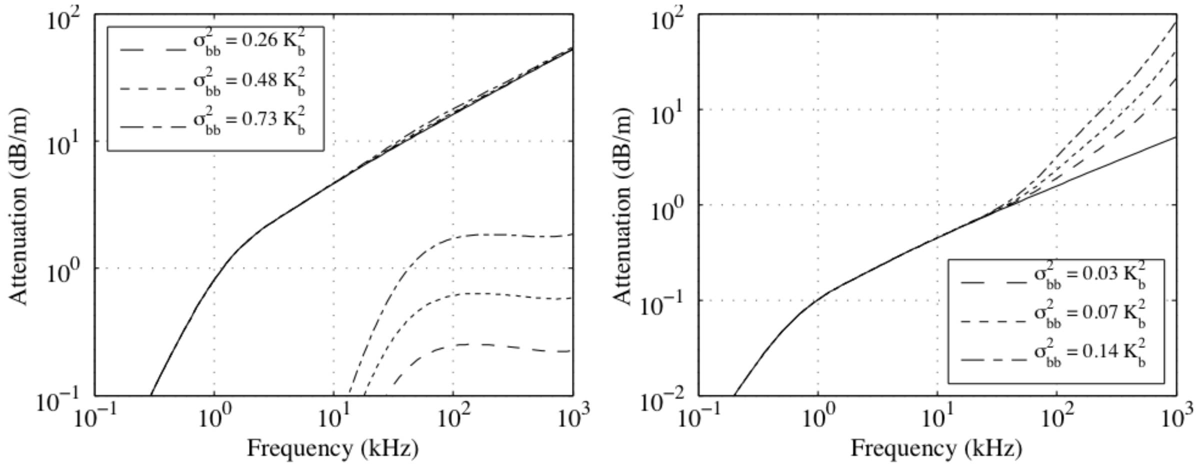

Figure 2. (a) Attenuation for the SAX99 sediment assuming an exponential correlation for the frame bulk modulus variations. The lower set of curves is the contribution to the attenuation from the scattering from the fast compressional wave into slow compressional waves. (b) Attenuation for a sintered glass bead pack assuming an exponential correlation for the frame bulk modulus variations. The black curve in both plots is the attenuation for the homogenous medium.

While the frame modulus heterogeneities may not play a significant role in sound propagation through a sand sediment, it appears that variations in the porosity may produce significant scattering and hence increased attenuation. When heterogeneities in the porosity are present, a propagating compressional wave can scatter energy into fast and slow compressional waves and also into shear waves. When the theory is applied to the SAX99 data, however, the dominant scattering occurs between coherent and incoherent fast compressional waves. This suggested that by applying perturbation theory to the effective density fluid model (EDFM) it is possible to get an equivalent fit to the data using a simpler theory. The fits of both the perturbed Biot theory and perturbed EDFM to the SAX99 sound speed and attenuation is shown in Figure 3.

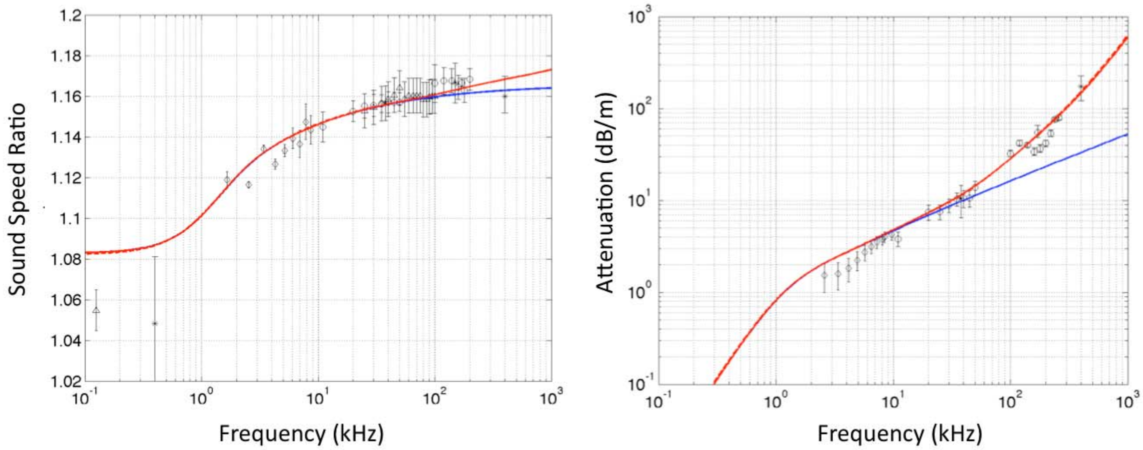

Figure 3. Comparisons of the perturbed Biot Theory (red dashed line) and perturbed EDFM (red solid line) to the SAX99 sound speed and attenuation. Both theories assume that the variations in the porosity follow an exponential correlation function with L = 2.5 mm and $\sigma^2 = 0.02\ \beta^2$, where L is the correlation length and σ^2 is the variance. The predictions of the unperturbed Biot Theory (blue dashed line) and the unperturbed Biot Theory (blue solid line) are also shown.

The dominance of the fast to fast wave scattering loss mechanism in the SAX99 sound speed and attenuation fits suggests that this loss mechanism may be connected to volume scattering from the sediment interface. To test this, a portion of the sand sediment at the test pond was manually smoothed flat by divers and then the residual roughness of this region was measured using the Laser-Line Scanner (LLS). Backscattering from this smoothed area was measured from 200 to 500 kHz. The predictions of perturbation theory using the sediment roughness measurements underestimates the backscattering over the entire frequency range for angles greater than the critical angle as shown in Figure 4. For frequencies greater than 275 kHz, the theory underestimates the scattering for subcritical grazing angles as well. Fits to the data using theories which incorporate volume scattering indicate that this may be the mechanism responsible for the observed scattering. Efforts are underway to determine if the same set of heterogeneity statistics can fit the sound speed, attenuation, and backcattering levels measured at the test pond.

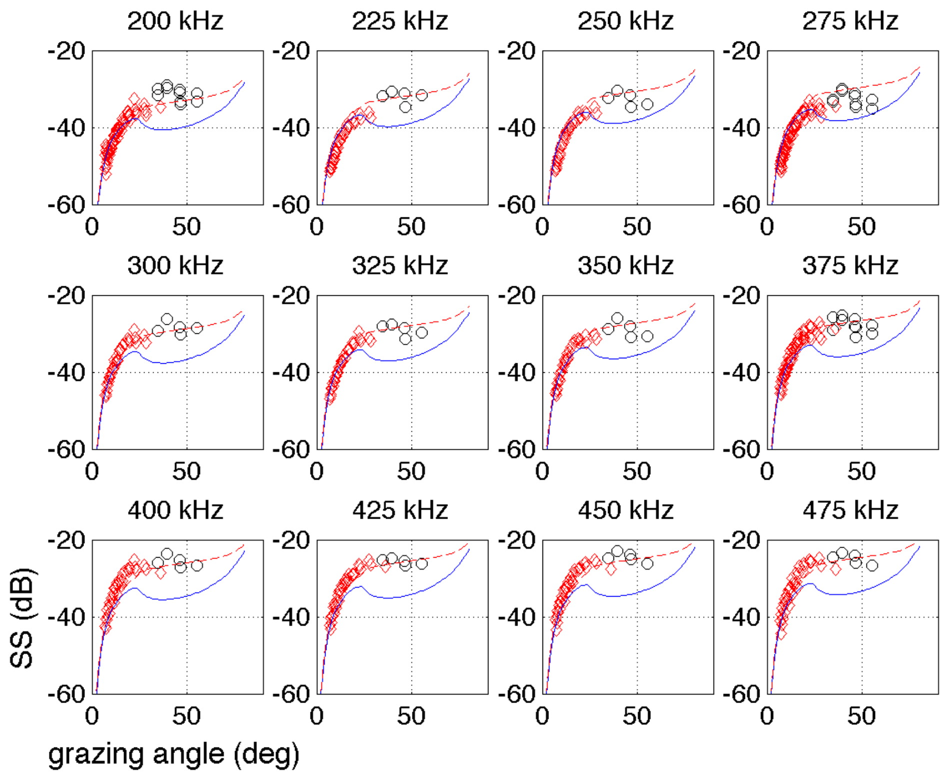

Figure 4. Data collected from the artificially smoothed sediment in the NSWC pond. The red and black circles indicate different height settings for the transducers. The blue lines are predictions of perturbation theory using the roughness spectra measured using the Laser-Line Scanner. The red dashed curves are a fit to the data assuming volume heterogeneities in the density and sound speed of the sediment.

IMPACT/APPLICATIONS

This work will potentially lead to the development of complete, physically-based models of sound propagation in sandy sediments by accounting for scattering losses which can supplement various proposed loss mechanisms such as grain-to-grain shearing.

RELATED PROJECTS

1. Title: High-Frequency Sound Interaction in ocean sediments, Grant# N00014-98-1-0040, E.I. Thorsos, PI. http://www.apl.washington.edu/projects/SAX04/summary.html The efforts of SAX04 were coordinated under this program. The measurement of sediment sound speed and attenuation at the SAX04 site was conducted under this program. The results of the analysis of this data will be used in the development of theories of sound propagation.

2. Title: APL-UW Component of: Evanescent Detection of Buried Targets, Grant# N00014-07-G-0557, S.G. Kargl, PI. The APL-UW rail tower was deployed in the NSWC-PC pond in the spring of 2009. This deployment was leveraged by mounting the bistatic array used during SAX04 to the front

of the rail tower. The collection of backscattering data took place between the primary data collection runs for this project.

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PUBLICATIONS

B.T. Hefner and D.R. Jackson, "Dispersion and attenuation due to scattering from heterogeneities the frame bulk modulus of a poroelastic medium," *Submitted for publication in J. Acoust. Soc. Am.*, (2009).